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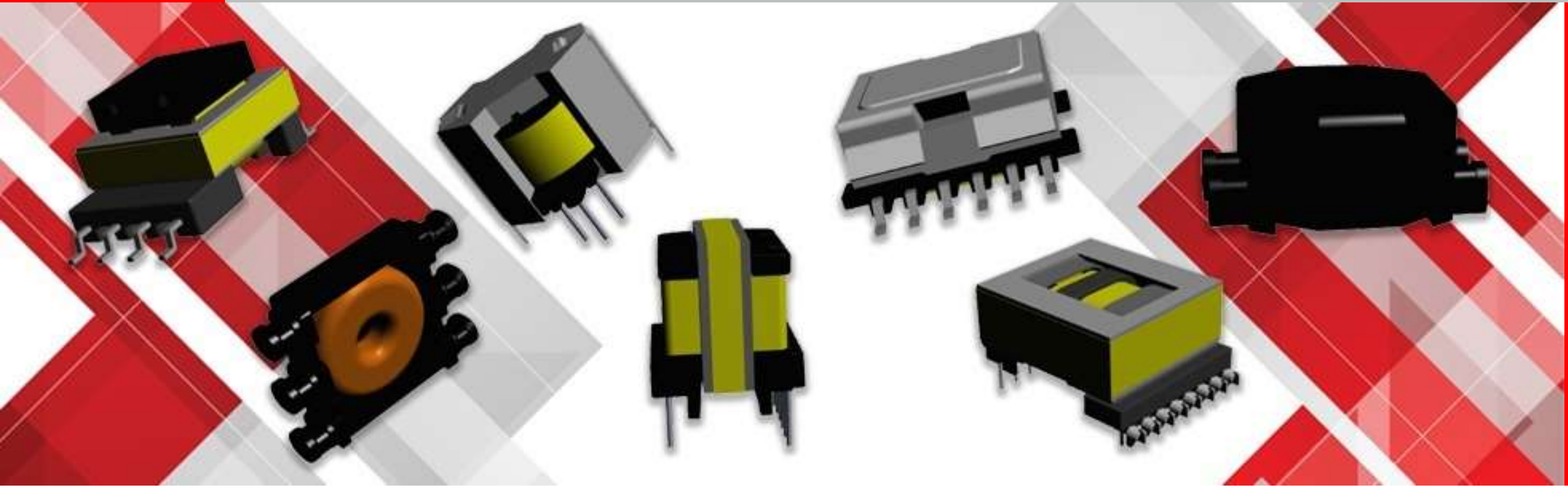
Transformer Design Considerations



Component Selection

Core

Bobbin

Wire

Tape

Clip

Adhesive

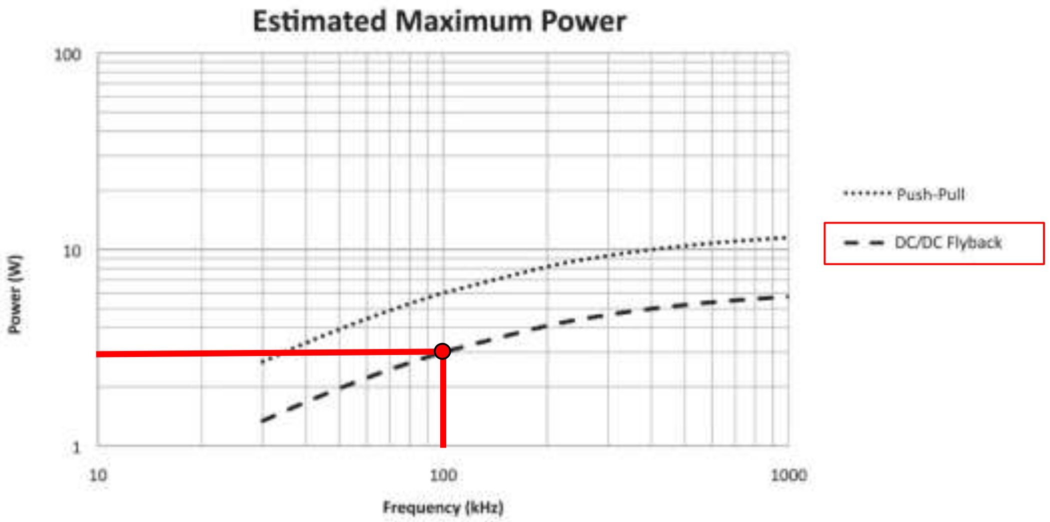
Varnish

Core Selection

- **Power vs Switching Frequency**

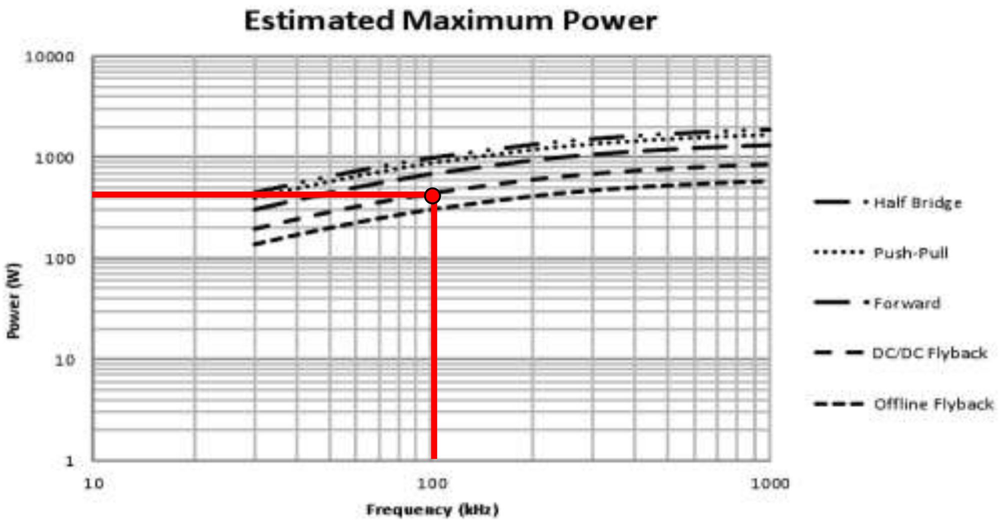
Low Power

EP7: For a DC-DC flyback operating at 100kHz, this core can supply up to 3W



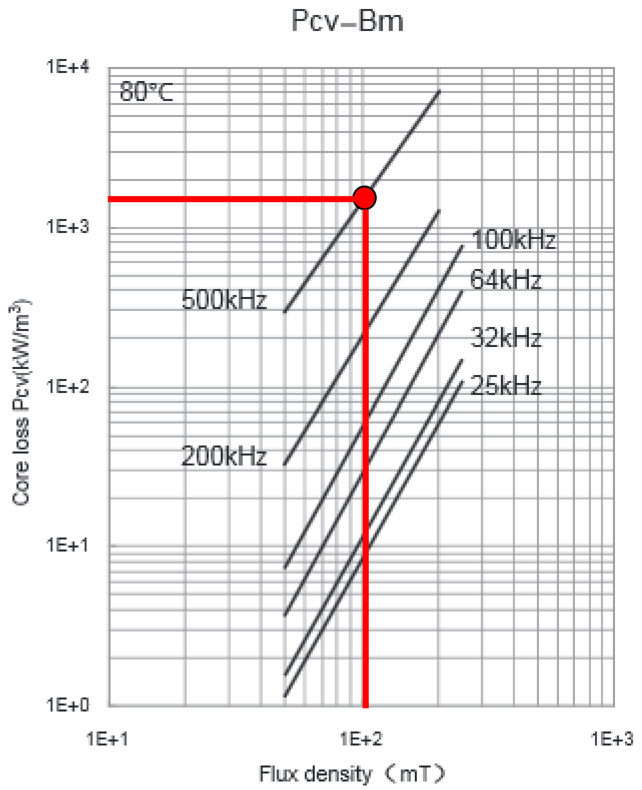
High Power

ETD39: For a DC-DC flyback operating at 100kHz, this core can supply up to 400W



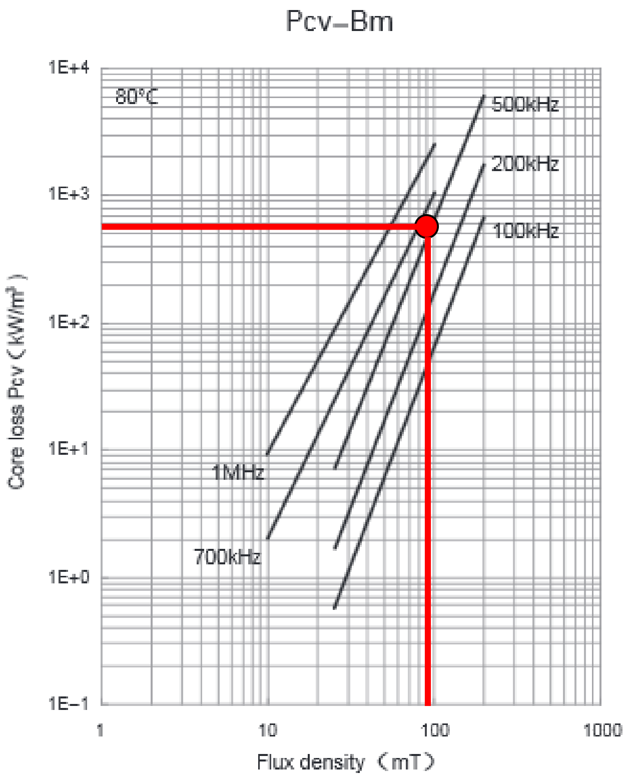
Core Selection

- **Operating frequency guides us to the right core material and core losses**



TP4 (TDG 2018: 20)

~1060 Pcv(KW/m3) loss @ 100mT, 500kHz



TP5 (TDG 2018: 36)

~700 Pcv(KW/m3) loss @ 100mT, 500kHz

Bobbin Selection – Material

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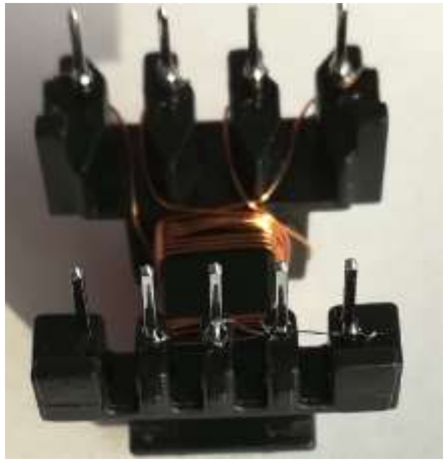
- **Thermoplastic (PBT, PET, LCP)**
  - ▲ Easy to mold
  - ▲ Flexible
  - ▼ Low melt point
  - ▼ Easily deformed

- **Thermoset (PM9820, AM-113, WH9100)**
  - ▲ High Temperature (soldering)
  - ▲ Robust
  - ▼ Less flexible
  - ▼ Difficult to mold



Wire Selection

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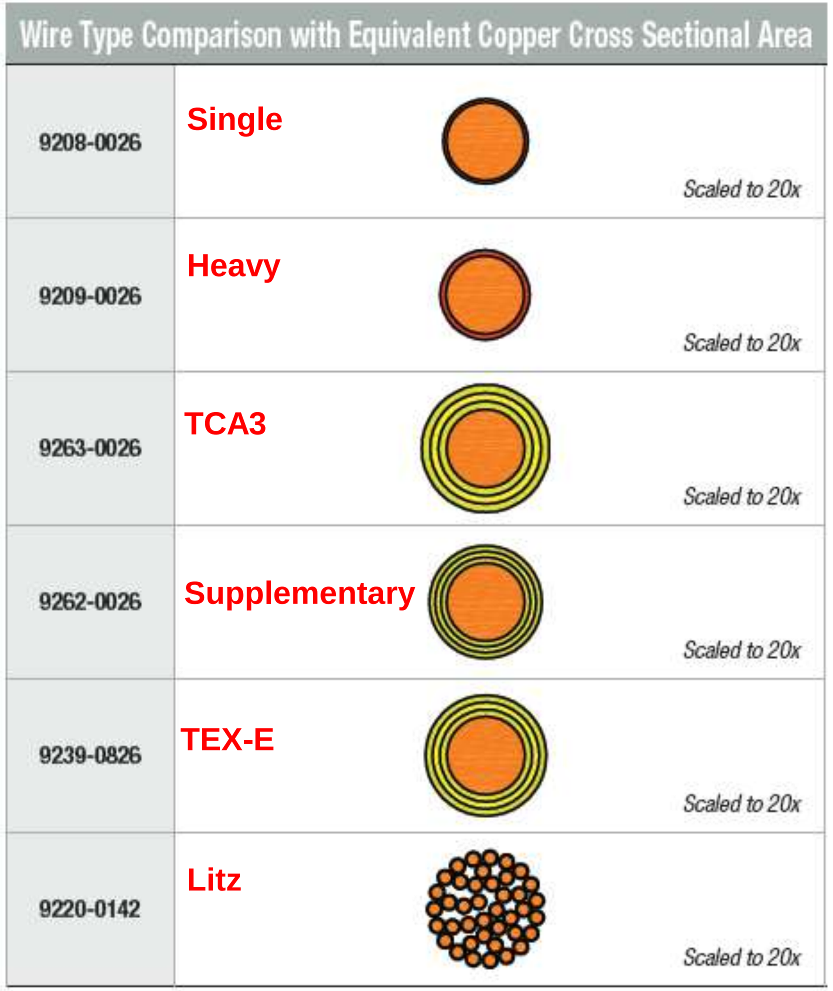
- **Chosen wire depends on safety grade and dielectric requirements**
  - Single insulation magnet wire
  - Heavy insulation magnet wire
  - Basic / Supplementary insulation
  - Triple Insulated Wire (TCA3 or TEX-E)
  - Fully Insulated Wire
  - Litz wire



Transformer's Parasitics

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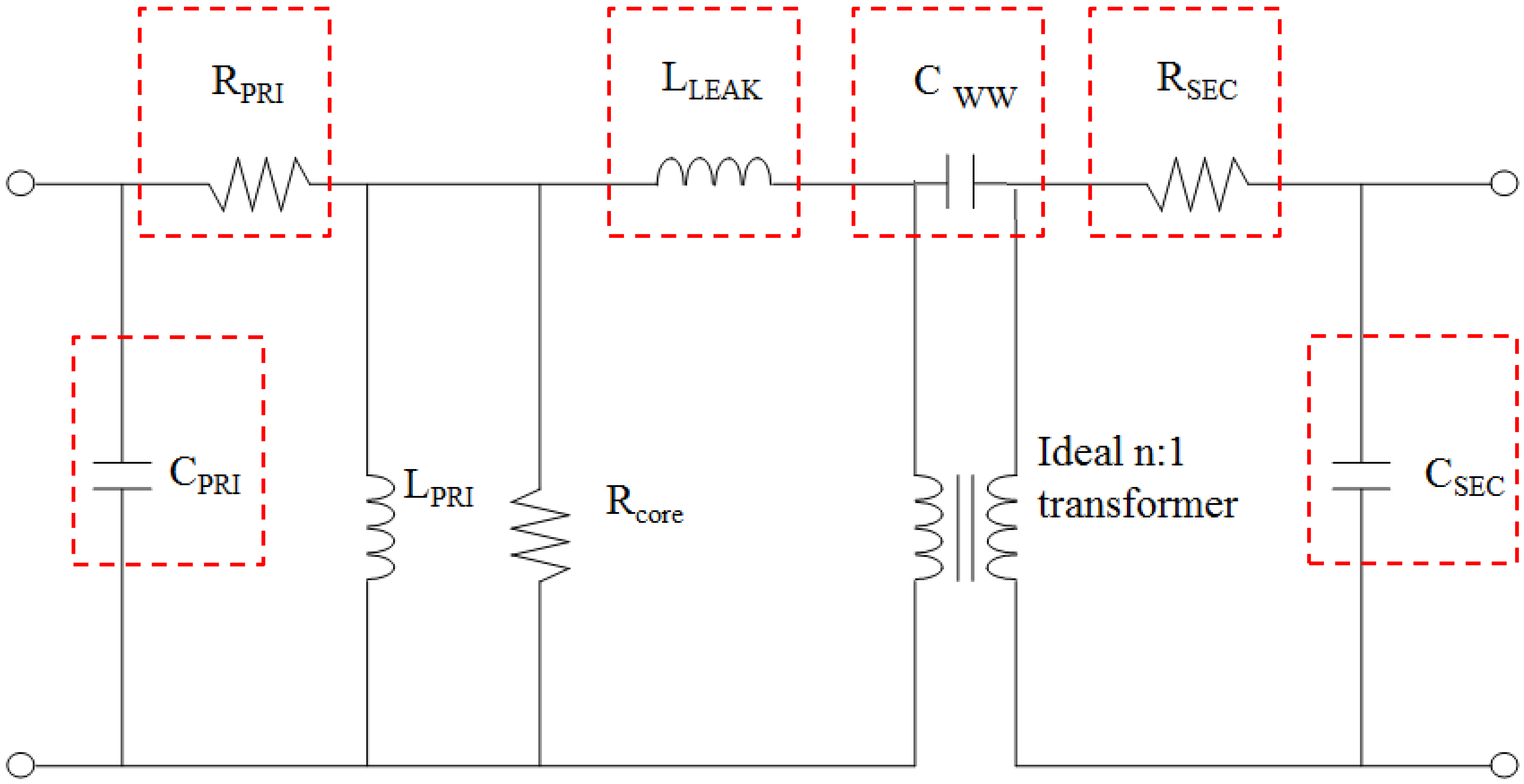
- **DC Resistance, Leakage Inductance and Inter/Intrawinding Capacitance**



DC Resistance and Capacitance

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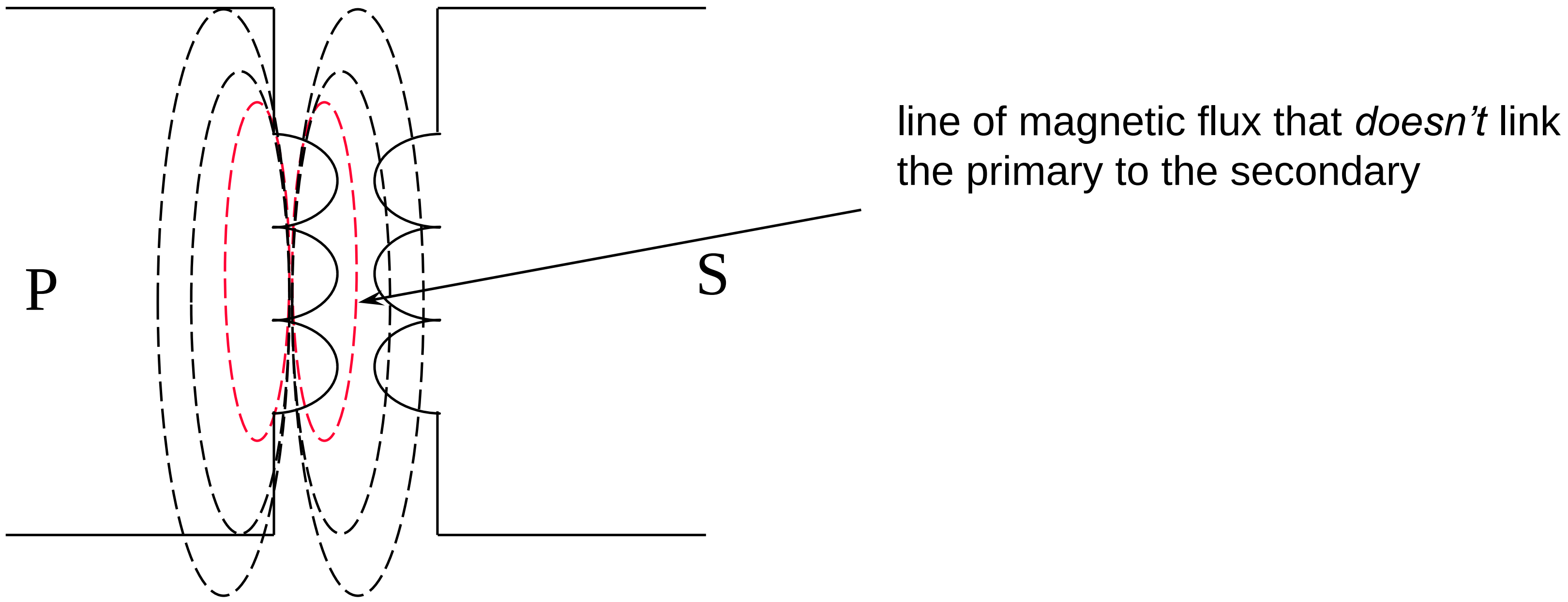
- **DC Resistance** is a direct function of wire thickness.
  The resistance can be reduced by using thicker wire or multiple strands in parallel

- **Intrawinding Capacitance** on the Primary side can increase switching losses.
  This can be reduced by using thicker insulated wire to increase the distance between turns.

- Split primary windings can result in unbalanced **interwinding capacitance** potentially leading to EMI issues but it is a prefer method to reduce leakage inductance .
  This can be reduced by separating the primary and secondary windings as much as possible, e.g. tape, shield or auxilliary wind between PRI and SEC.

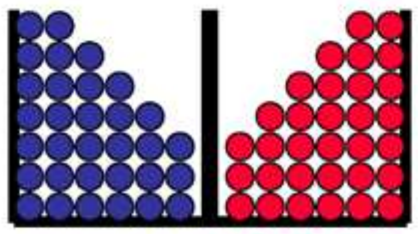
Leakage Inductance



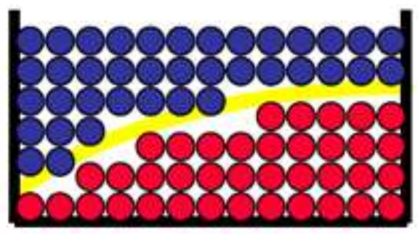
Leakage inductance is a measure of how much magnetic flux couples from the primary into the secondary. The greater the distance between the primary and the secondary, the fewer flux lines there will be to couple the two windings together. Fewer flux lines coupling the windings means larger values of leakage inductance.

Leakage Inductance

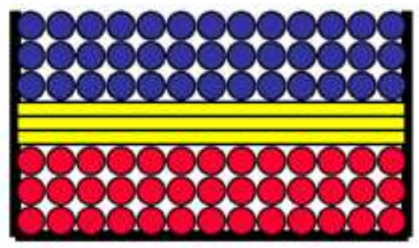
- **Common causes of leakage inductance**



- Centre-flange
- Sloping coils



- Sloping coils
- Uneven tape

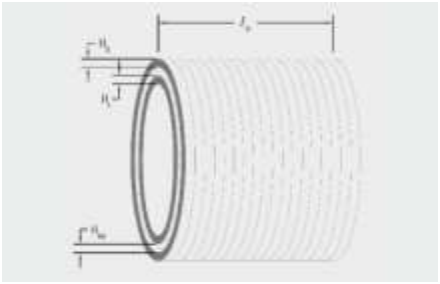


- Too many tape layers
- Tape too thick

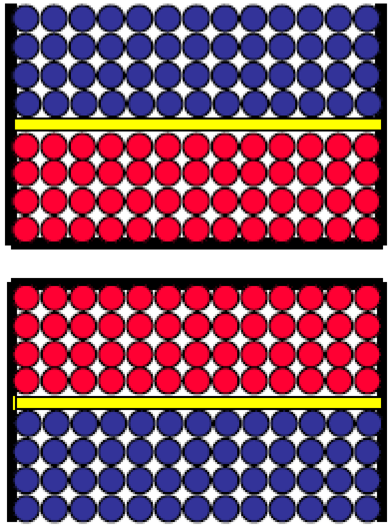
Leakage Inductance

- **Maximizing coupling between PRI and SEC**

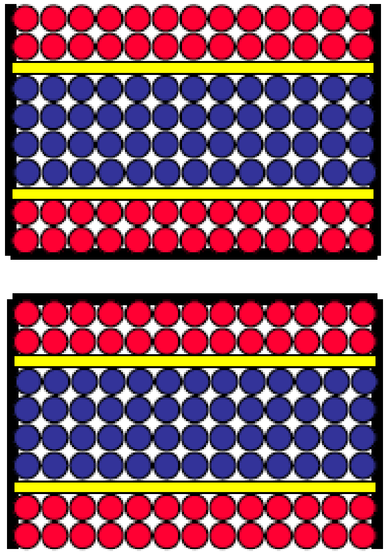
$$L=\frac{3.194 \cdot MLT \cdot N \cdot (h+b/3)}{10^5 \cdot w \cdot \boxed{s^2}}$$



MLT = Mean Length Turn
N = Number of Turns
h = Thickness between winds (note this can be wire to wire and lay
layer)
b = Build of wire
w = Width of winding (centering factor)
s = Number of splits



Consecutive windings primary and secondary



Split primary to sandwich secondary

To improve the coupling between the windings we can sandwich the first winding around the second. This reduces the average distance between the windings and results in 1/4th the original value of leakage inductance – at the expense of more winding labor.

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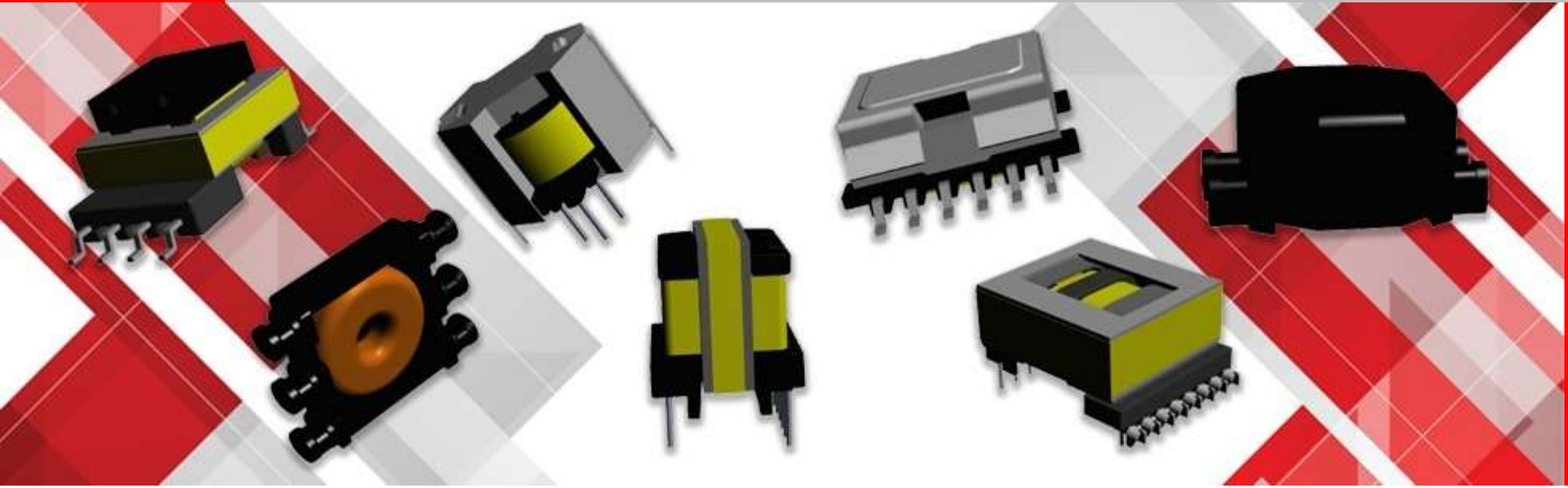
Design for Safety



Common Safety Standards

- **IEC60950-1** Safety of information Technology Equipment
- **IEC60601-1** Safety of Medical Electrical Equipment
- **IEC61010-1** Safety of Measurement Control and Laboratory Equipment
- **IEC61558-1** Safety of Power transformers and Power Supplies.
- The New safety standard **IEC62368-1** -> Audio Video and information technology equipment

- **UL1446** Electrical Insulation Systems (Temperature class only)

Common Inputs Required

- **Material Group according to Comparative Tracking Index (CTI)**
- **Insulation Grade**
- **Pollution Degree**
- **Overvoltage Category**
- **RMS Working Voltage**
- **Peak Working Voltage**
- **RMS Mains Voltage**

Material Group – Tracking Index

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- **The voltage which causes tracking after 50 drops of 0.1% ammonium chloride solution have fallen on the material. The results of testing at 3 mm thickness are considered representative of the material's performance in any thickness.**

- **Tracking is an electrical breakdown on the surface of an insulating material. A large voltage difference gradually creates a conductive leakage path across the surface of the material by forming a carbonized track.**

Best material → I

IEC rating(Material Group)	UL rating (PLC)	Comparative Tracking Index (volts)
I	0	≥ 600V
II	1	400V ≤ CTI < 600V
IIIa	2	250V ≤ CTI < 400V
	3	175V ≤ CTI < 250V
IIIb	4	100V ≤ CTI < 175V
None	5	0V ≤ CTI < 100V

Insulation Grades

- **Several grades of insulation are defined for each standard**
  - Functional Insulation - Is only necessary for the correct functioning of equipment and does not provide any protection against electric shock.
  - Basic Insulation - Insulation applied to live parts to provide basic protection against electric shock.
  - Supplementary Insulation - Independent insulation applied in addition to basic insulation in order to provide protection against electric shock in the even of a failure of basic insulation.
  - Double Insulation - Comprising both basic insulation and supplementary insulation.
  - Reinforced Insulation - Single insulation system applied to live parts which provides a degree of protection against electric shock equivalent to double insulation.

Pollution Degree

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IEC 60950-1 defines pollution degree as below:

- **Pollution Degree 1** applies where there is no pollution or only dry, non-conductive pollution. The pollution has no influence. Normally, this is achieved by having components and subassemblies adequately enclosed by enveloping or hermetic sealing so as to exclude dust and moisture (see 2.10.12).

- **Pollution Degree 2** applies where there is only non-conductive pollution that might temporarily become conductive due to occasional condensation. It is generally appropriate for equipment covered by the scope of this standard.

- **Pollution Degree 3** applies where a local environment within the equipment is subject to conductive pollution, or to dry non-conductive pollution that could become conductive due to expected condensation.

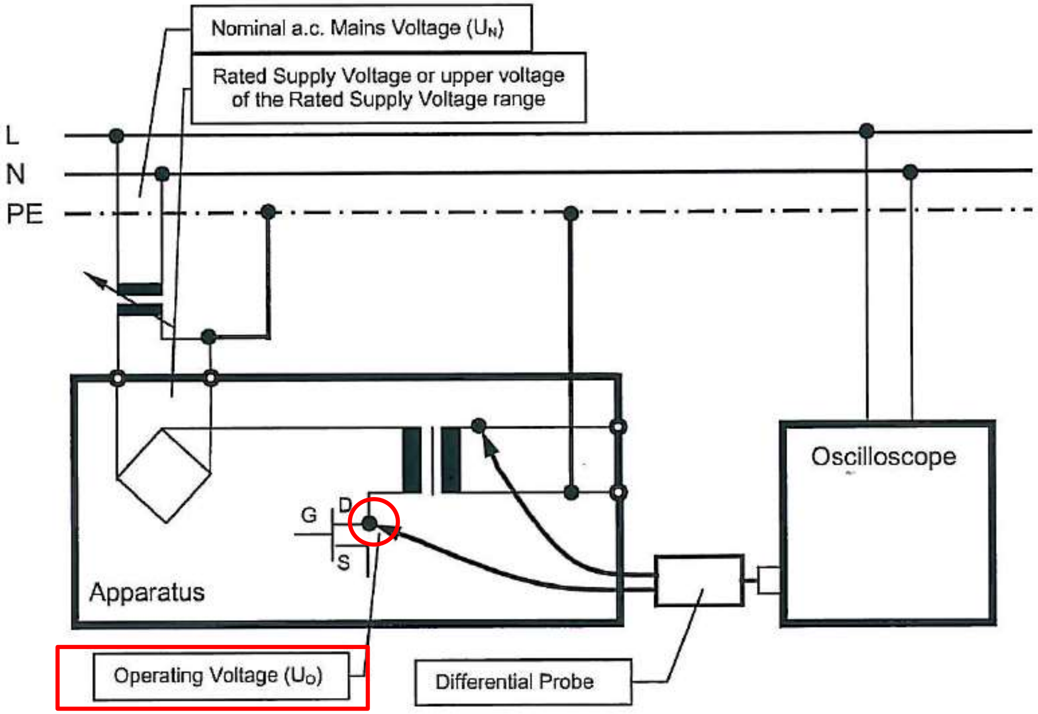
Overvoltage Category

- **Overvoltage categories by IEC 60950-1**

Overvoltage category	Equipment and its point of connection to the AC MAINS SUPPLY	Examples of equipment
IV	Equipment that will be connected to the point where the AC MAINS SUPPLY enters the building	Electricity meters Communications information technology equipment for remote electricity metering
III	Equipment that will be an integral part of the building wiring	Socket-outlets, fuse panels and switch panels Power monitoring equipment
II	PLUGGABLE or PERMANENTLY CONNECTED EQUIPMENT that will be supplied from the building wiring	Household appliances, portable tools, home electronics Most information technology equipment used in the building
I	Equipment that will be connected to a special AC MAINS SUPPLY in which measures have been taken to reduce transients	Information technology equipment supplied via an external filter or a motor driven generator

Working Voltage

- **The highest voltage that the insulation under consideration is or can be subjected to under normal operating conditions.**



VDE: Instruction – Operating voltage (2010:1)

Creepage and Clearance

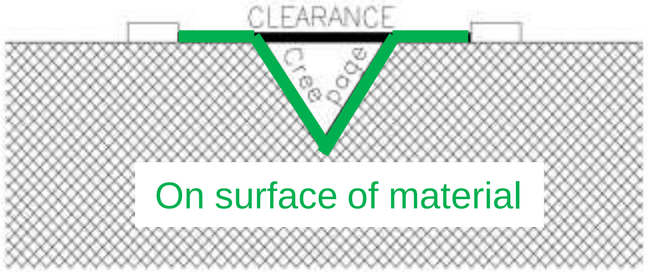
- **Creepage and Clearances distances (safety distances) determined by:**

  - Working voltage (maximum system voltage between PRI & SEC)
  - Bobbin Material Group (Comparative Tracking Index “CTI”)
  - Insulation grade (Basic, Supplementary, Reinforced)

- **Example for safety standard IEC60950-1:**

  Working Voltage = 320 Vrms
  Working votlage peak = 400 Vpeak
  Main supply voltage = 240Vrms
  Material Group = 3
  Overvoltage CAT = II
  Insulation Grade = Basic Insulation

  From safety standard tables:
  Dielectric Voltage = 1500VAC, Creepage = 3.2mm, Clearance = 2mm



Creepage and Clearance

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- **Minimum creepage distances for** **Basic insulation:**

CREEPAGE DISTANCES in mm

RMS WORKING VOLTAGE up to and including V	Pollution degree 1 [a]	2	1 [a]	2			3		
	Material group: Printed boards		Other materials						
	I, II, IIIa, IIIb	I, II, IIIa	I, II, IIIa, IIIb	I	II	IIIa, IIIb	I	II	IIIa, IIIb (see Note)
10	0,025	0,04	0,08	0,4	0,4	0,4	1,0	1,0	1,0
12,5	0,025	0,04	0,09	0,42	0,42	0,42	1,05	1,05	1,05
16	0,025	0,04	0,1	0,45	0,45	0,45	1,1	1,1	1,1
20	0,025	0,04	0,11	0,48	0,48	0,48	1,2	1,2	1,2
25	0,025	0,04	0,125	0,5	0,5	0,5	1,25	1,25	1,25
32	0,025	0,04	0,14	0,53	0,53	0,53	1,3	1,3	1,3
40	0,025	0,04	0,16	0,56	0,8	1,1	1,4	1,6	1,8
50	0,025	0,04	0,18	0,6	0,85	1,2	1,5	1,7	1,9
63	0,04	0,063	0,2	0,63	0,9	1,25	1,6	1,8	2,0
80	0,063	0,10	0,22	0,67	0,9	1,3	1,7	1,9	2,1
100	0,1	0,16	0,25	0,71	1,0	1,4	1,8	2,0	2,2
125	0,16	0,25	0,28	0,75	1,05	1,5	1,9	2,1	2,4
160	0,25	0,40	0,32	0,8	1,1	1,6	2,0	2,2	2,5
200	0,4	0,63	0,42	1,0	1,4	2,0	2,5	2,8	3,2
250	0,56	1,0	0,56	1,25	1,8	2,5	3,2	3,6	4,0
320	0,75	1,6	0,75	1,6	2,2	3,2	4,0	4,5	5,0
400	1,0	2,0	1,0	2,0	2,8	4,0	5,0	5,6	6,3
500	1,3	2,5	1,3	2,5	3,6	5,0	6,3	7,1	8,0
630	1,8	3,2	1,8	3,2	4,5	6,3	8,0	9.0	10
800	2,4	4,0	2,4	4,0	5,6	8,0	10	11	12,5
1 000	3,2	5,0	3,2	5,0	7,1	10	12,5	14	16

IEC 60950-1 (2005:214)

Creepage and Clearance

- **Minimum clearances for insulation in primary circuits and between primary and secondary circuits**

CLEARANCES in mm

PEAK WORKING VOLTAGE [a] up to and including V	MAINS TRANSIENT VOLTAGE 1 500 V [c] Pollution degree 1 and 2 [b] F	B/S	R	1 500 V [c] 3 F	B/S	R	2 500 V [c] 1 and 2 [b] F	B/S	R	2 500 V [c] 3 F	B/S	R	4 000 V [c] 1, 2 [b] and 3 F	B/S	R
71	0,4	1,0 (0,5)	2,0 (1,0)	0,8	1,3 (0,8)	2,6 (1,6)	1,0	2,0 (1,5)	4,0 (3,0)	1,3	2,0 (1,5)	4,0 (3,0)	2,0	3,2 (3,0)	6,4 (6,0)
210	0,5	1,0 (0,5)	2,0 (1,0)	0,8	1,3 (0,8)	2,6 (1,6)	1,4	2,0 (1,5)	4,0 (3,0)	1,5	2,0 (1,5)	4,0 (3,0)	2,0	3,2 (3,0)	6,4 (6,0)
420	F 1,5 B/S 2,0 (1,5) R 4,0 (3,0)												2,5	3,2 (3,0)	6,4 (6,0)
840	F 3,0 B/S 3,2 (3,0) R 6,4 (6,0)														
1 400	F/B/S 4,2 R 6,4														
2 800	F/B/S/R 8,4														
7 000	F/B/S/R 17,5														
9 800	F/B/S/R 25														
14 000	F/B/S/R 37														
28 000	F/B/S/R 80														
42 000	F/B/S/R 130														

The values in the table are applicable to FUNCTIONAL INSULATION (F) if required by 5.3.4 a) (see 2.10.1.3), BASIC INSULATION (B), SUPPLEMENTARY INSULATION (S) and REINFORCED INSULATION (R).

The values in parentheses apply to BASIC INSULATION, SUPPLEMENTARY INSULATION or REINFORCED INSULATION only if manufacturing is subjected to a quality control programme that provides at least the same level of assurance as the example given in Clause R.2. DOUBLE INSULATION and REINFORCED INSULATION shall be subjected to ROUTINE TESTS for electric strength.

If the PEAK WORKING VOLTAGE exceeds the peak value of the AC MAINS SUPPLY voltage, linear interpolation is permitted between the nearest two points, the calculated minimum CLEARANCE being rounded up to the next higher 0,1 mm increment.

[a] If the PEAK WORKING VOLTAGE exceeds the peak value of the AC MAINS SUPPLY voltage, see 2.10.3.3 b) regarding additional CLEARANCES.

[b] It is not required to pass the tests of 2.10.10 for Pollution Degree 1.

[c] The relationship between MAINS TRANSIENT VOLTAGE and AC MAINS SUPPLY voltage is given in Table 2J.

IEC 60950-1 (2005:199)

Examples safety calculator

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- **WE Midcom Safety calculator for calculation of creepage and clearance (example for 60950-1)**

  - Material Group: 3
  - Insulation Grade: Reinforced
  - Pollution Degree: 2
  - Overvoltage Category: II
  - RMS Working Voltage: 265Vrms
  - Peak Working Voltage: 400V
  - RMS Mains Voltage: 265Vrms

Safety Caclulator

Dielectric Voltage Required = 3000VAC
Creepage Distance Required = 5.3 mm
Clearance Distance Required = 4 mm

  - Material Group: 3
  - Insulation Grade: Basic
  - Pollution Degree: 2
  - Overvoltage Category: II
  - RMS Working Voltage: 265Vrms
  - Peak Working Voltage: 400V
  - RMS Mains Voltage: 265Vrms

Safety Caclulator

Dielectric Voltage Required = 1500VAC
Creepage Distance Required = 2.7 mm
Clearance Distance Required = 2 mm

Insulated Wire

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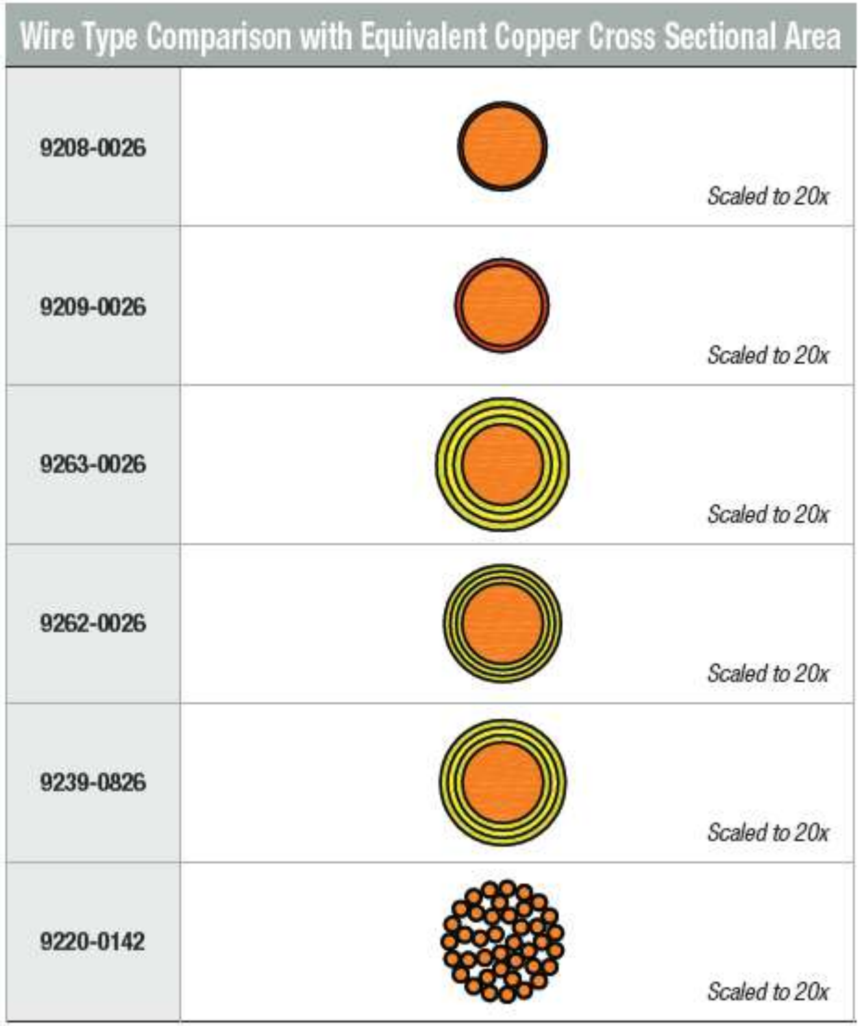
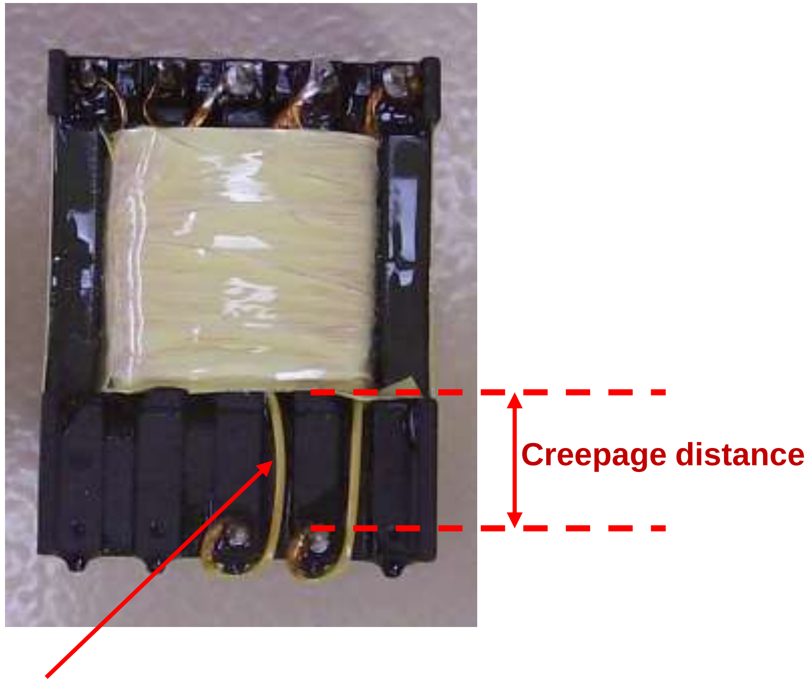
- **Triple Insulated Wire (TCA3 155ºC Class)**
  - ▲ Internal safety distances are easily met.
  - ▲ Full winding width of bobbin available
  - ▼ Not Automatable - (x2) Hand strip & terminate operations per wire
  - ▼ Material cost higher than magnet wire
  - ▼ Priced by length not weight - (2 x TIW = 2 x $$$)
- **Triple Insulated Wire (TEX-E 130ºC UL Class)**
  - ▲ Reduced diameter compared to TCA3 – more turns less cost
  - ▲ Approved by UL and VDE (extra tests may be required)
  - ▼ Not automatable
- **Fully Insulated Wire (FIW 180ºC Class)**
  - ▲ Lower cost (priced by weight)
  - ▲ Automatable (for < AWG30)
  - ▼ Only able to be used for 61558-2-16 designs with only VDE approval (not recognized by UL)
- **PFA Reinforced Insulation (180ºC Class)**
  - ▲ Higher temp rating – prefered for SMD package

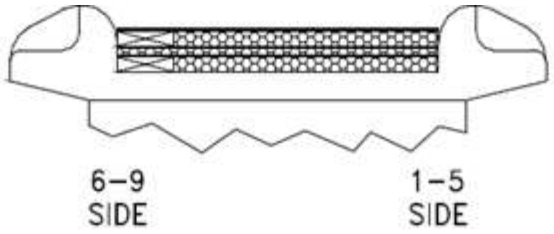


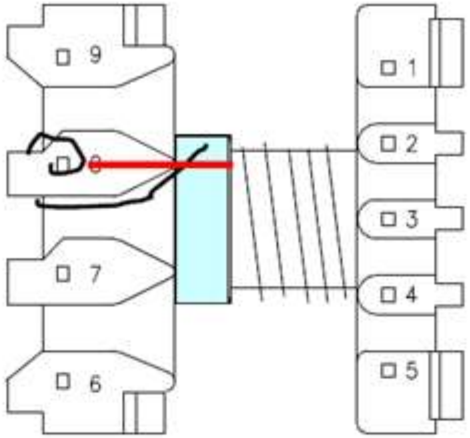
How to Achieve Creepage Distances

- **Use extended rail bobbin and / or margin tape to increase distance from SEC pins to PRI winding**



Triple Insulated Wire on SEC to insulate windings





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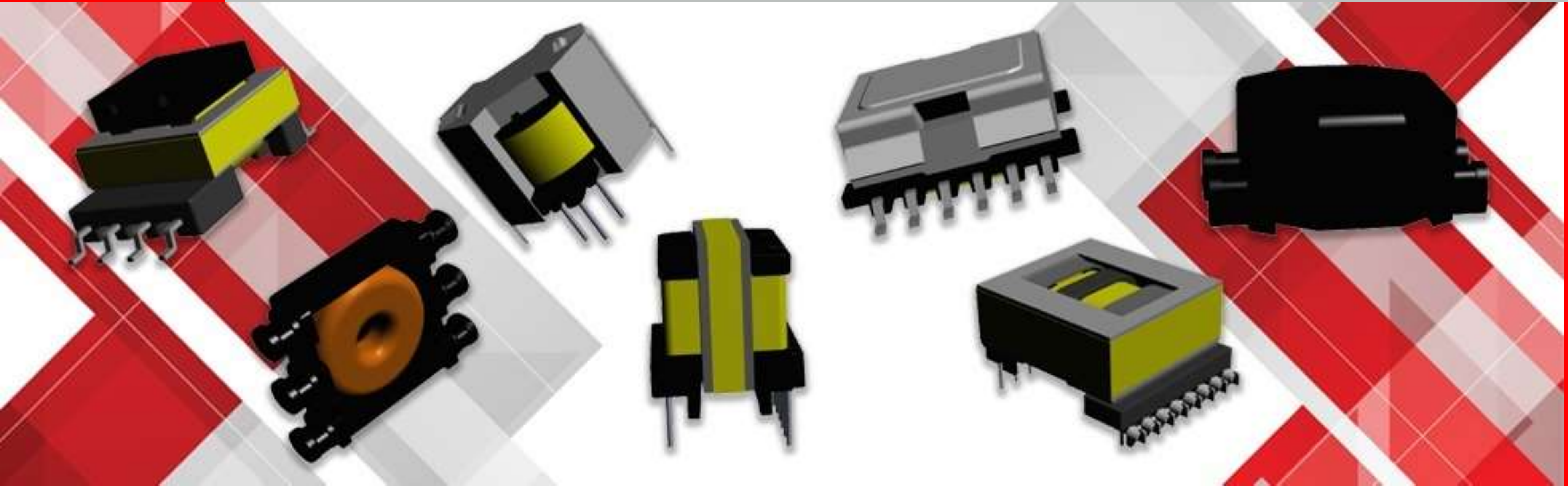
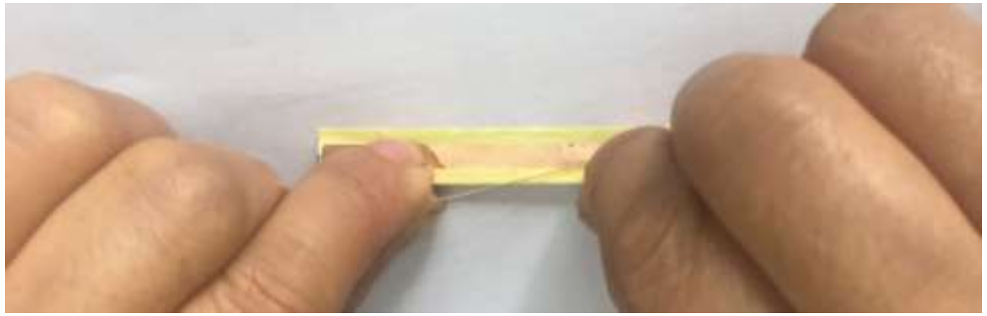
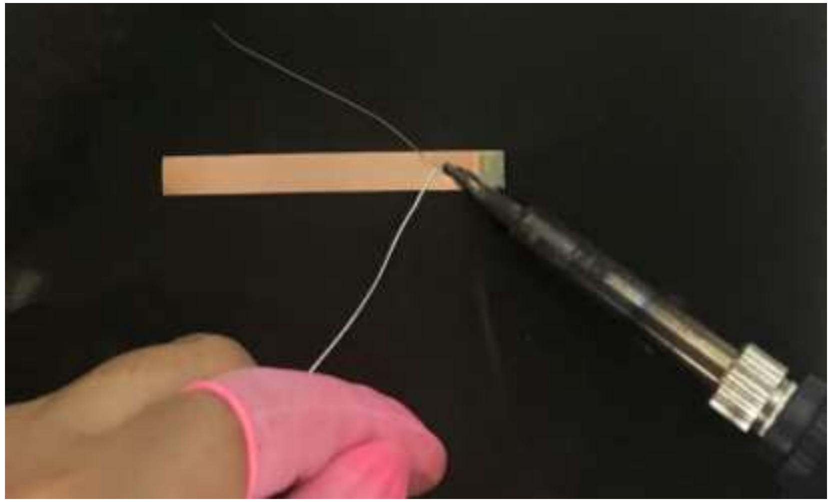
Design For EMC



Internal Copper foil shielding

- **Copper foil is „cuffed“ with tape and connected to system ground**
  - ▲ Shields both conducted and radiated noise
  - ▼ Shield must be prepared - labour intensive
  - ▼ No auto winding possible

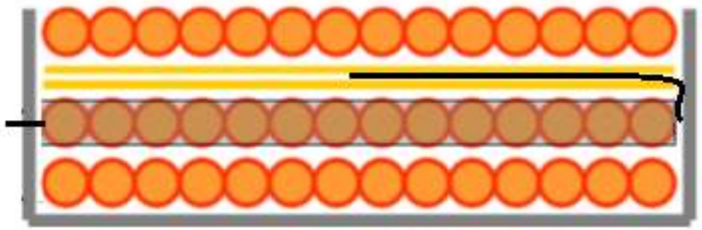




Internal wire wound shielding

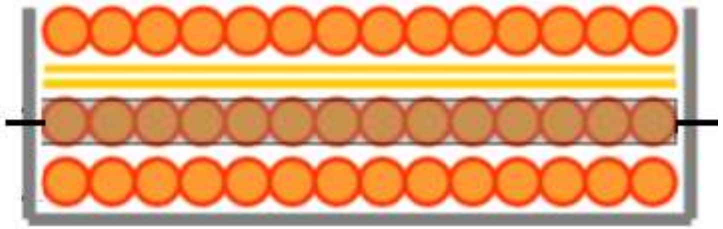
- **Compact single layer, one end connected to pin and the other buried**

▲ Shields both conducted and radiated noise
▼ Burying lead is manual process



- **For automation (and therefore lower cost) both ends of wire shield should be terminated to a pin, can either be with dragback or on other bobbin rail if safety distance allows for this**

▲ Shields both conducted and radiated noise
▲ Fully automatable



External Shielding - Flux Band

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- **Copper foil is wrapped around coil and core and left floating**

▲ Can be added after system level EMC test

▼ Shields radiated noise only
▼ Usually more expensive than internal wire wound shield

External Shielding – core Grounding

- **Flying lead (19) connected to copper foil (20) and connected to core using conductive adhesive. Can then be connected to system ground**

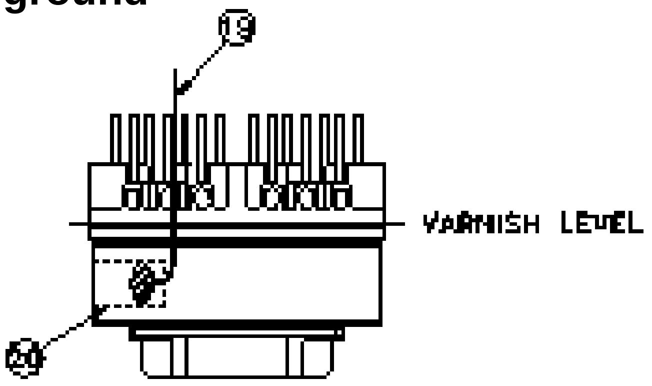

FIGURE 2

▲ Can be added to existing transformer if required after EMC test
▲ Good results seen compared to flux band solution

▼ Expensive compared to internal wire wound shield

External Shielding – closed core

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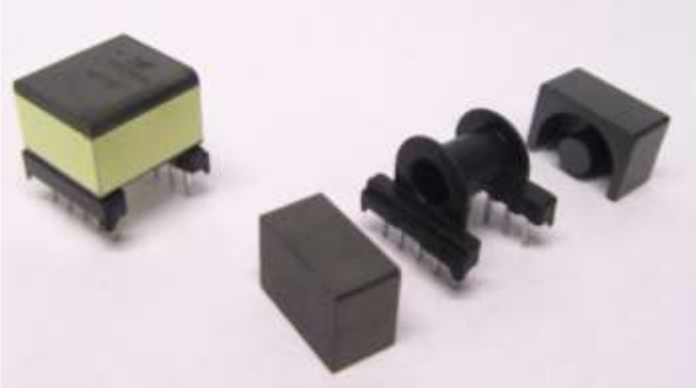
- **EP7 enclosed core provides shielding properties due to closed core**



▲ Little to no cost adder
▲ Build in solution

External Shielding – cap

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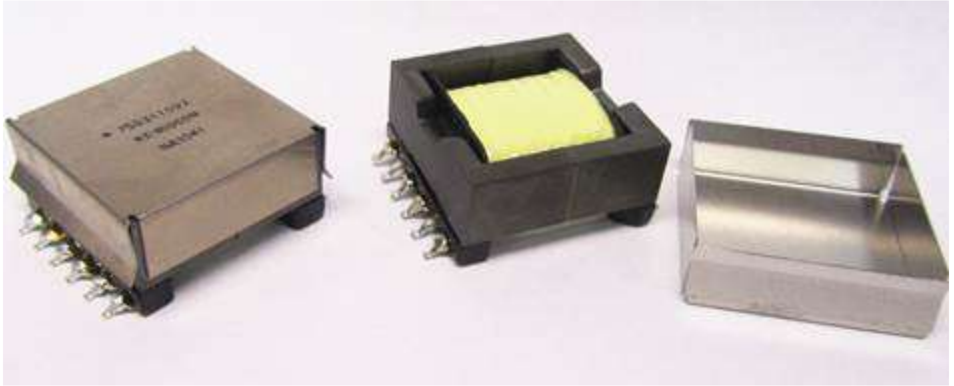
- **EFD 20 with external shield**



▲ Easy to assemble
▲ Can be added after design

▼ Shielding funtion only secondary (primary purpose pick and place)

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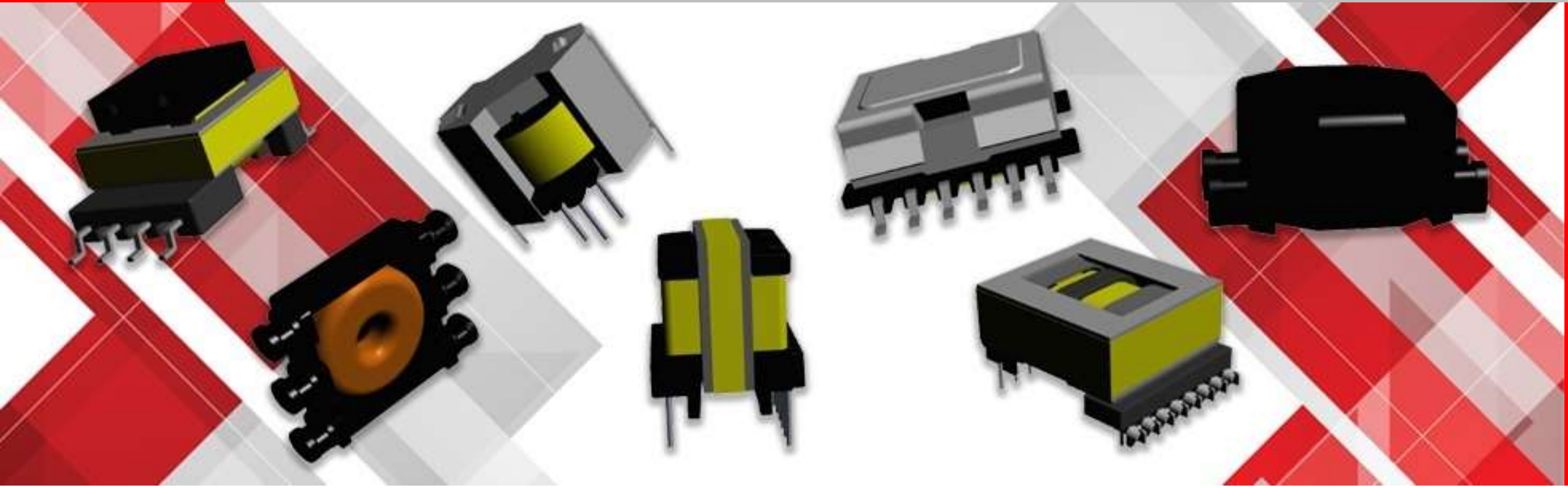
Design For Manufacturing



Why do we do DFM?

- **To increase reliability**
  - Adapt the design to use proven and repeatable processes

- **To reduce cost**
  - Use automated processes where possible
  - Reduce scrap

- **To reduce lead time**
  - Higher throughput using standard processes
  - Reduce rework
  - Use standard components

Transformer Manufacturing Processes

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- Winding
- Termination
- Soldering

Winding

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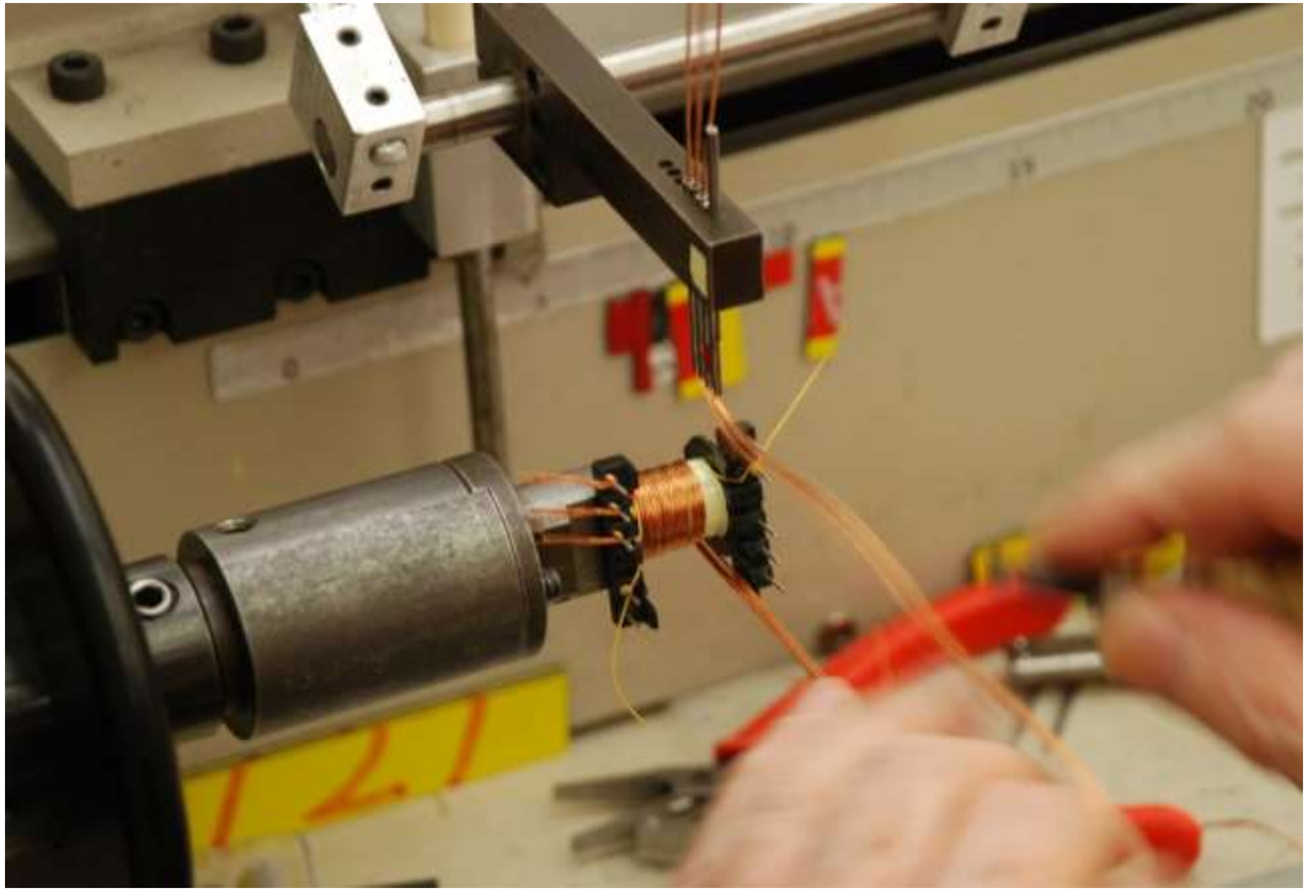
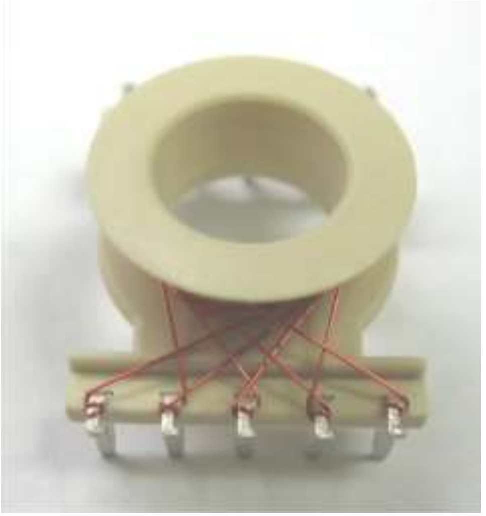
Considerations:

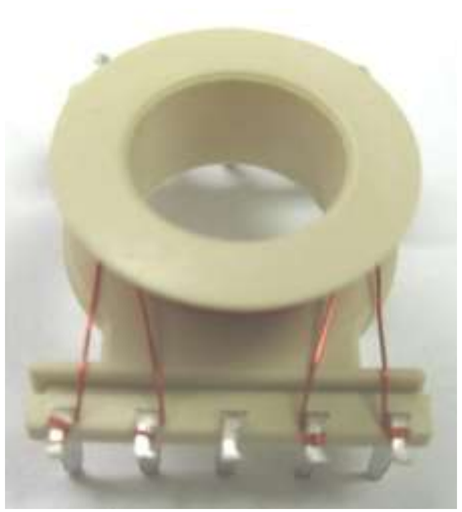
- **Pinout**
- **Layering**
- **Dragbacks**



Pinout – Wires crossing



Wire crossings can cause both mechanical and dielectric stress



This is the ideal pin assignment

Wire Dragbacks

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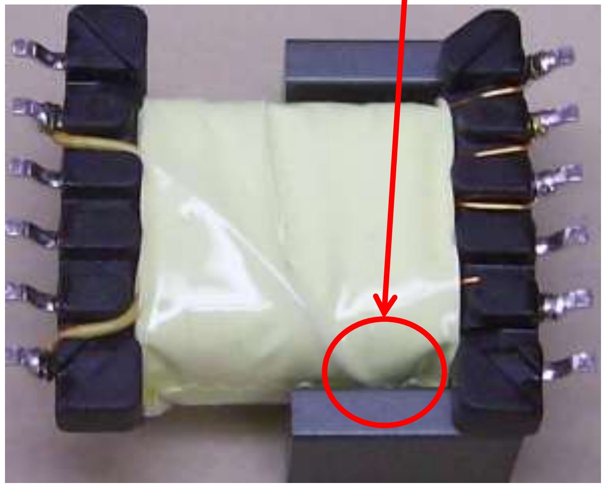
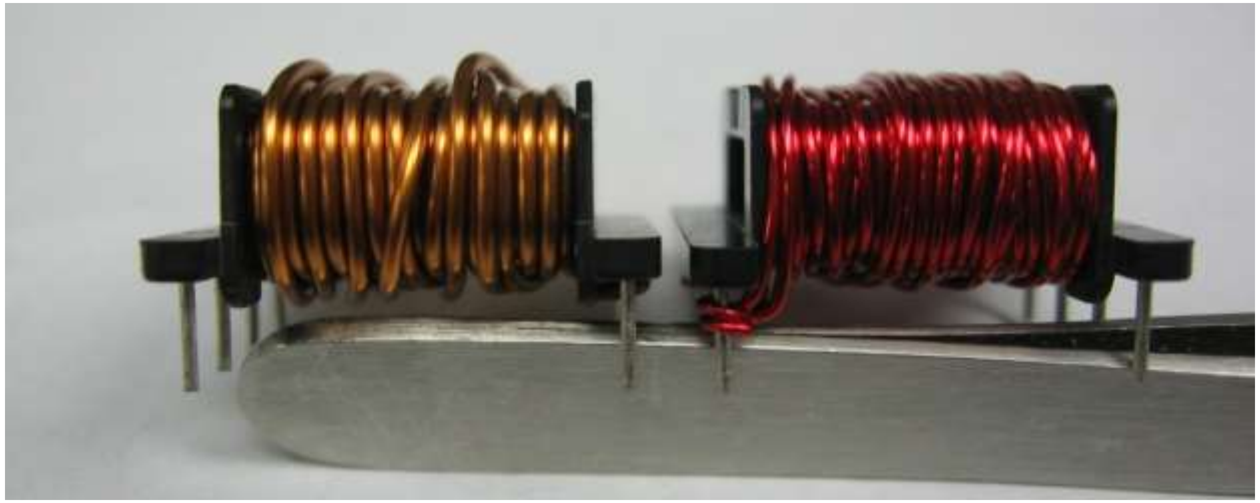
- **Dragbacks can be damaged by winding pressure from subsequent layers**
  - Start tape before dragback (higher labour)
- **90° dragbacks increase labor and may need extra tape**
- **Spiral dragbacks can cause core fit issues**

Potential core fit issue here



Layering

- **Adjust wire diameter and number of strands to fill layers**



The coil on the right uses a two-bi winding to achieve the same DC resistance, but better layering.

- **Choose pinout that promotes good layering**
  - Same rail pinout for even number of layers
  - Cross bobbin pinout for odd number of layers

Termination

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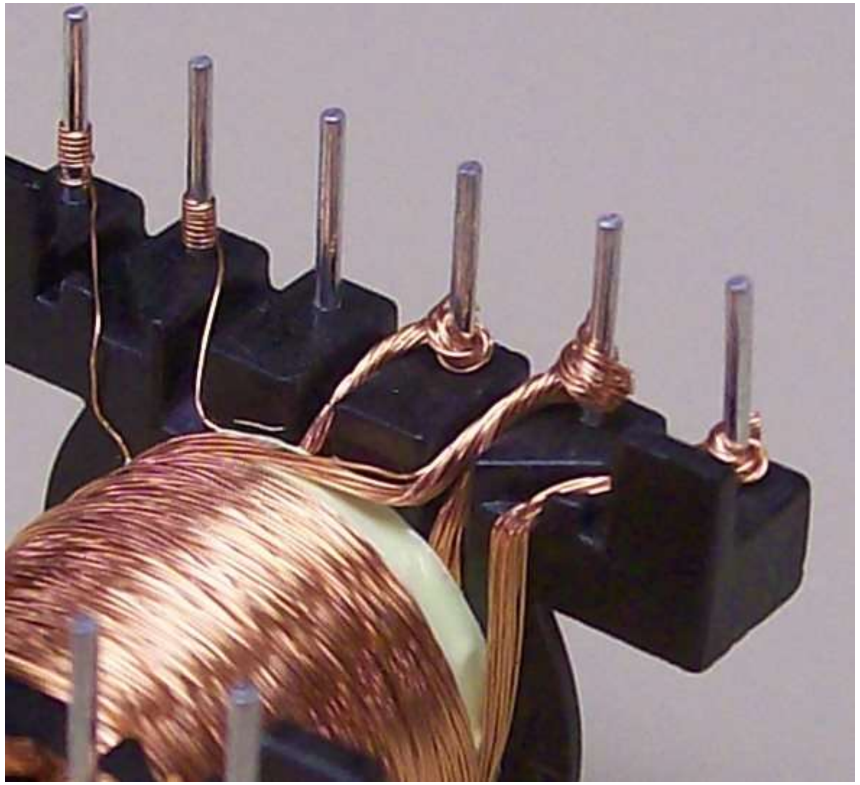
- **Specify wire and pin combinations that can utilize pull-break termination if possible**
  - Pins with sharp edges are more suitable for pull breaking
  - Automated winding requires pull breaking

- **For very heavy wire, through hole bobbins may be required**

- **Avoid heavy wire on surface mount terminals**
  - Co-planarity issues
  - Height issues
  - Use parallel winding splits and extra terminals for high current windings



Soldering

- **A large single strand is more difficult to solder than multiple lighter strands**

  - Large strands: more heat, more time - more insulation damage

- **Avoid using heavy or litz windings on same bobbin rail with fine wire windings**

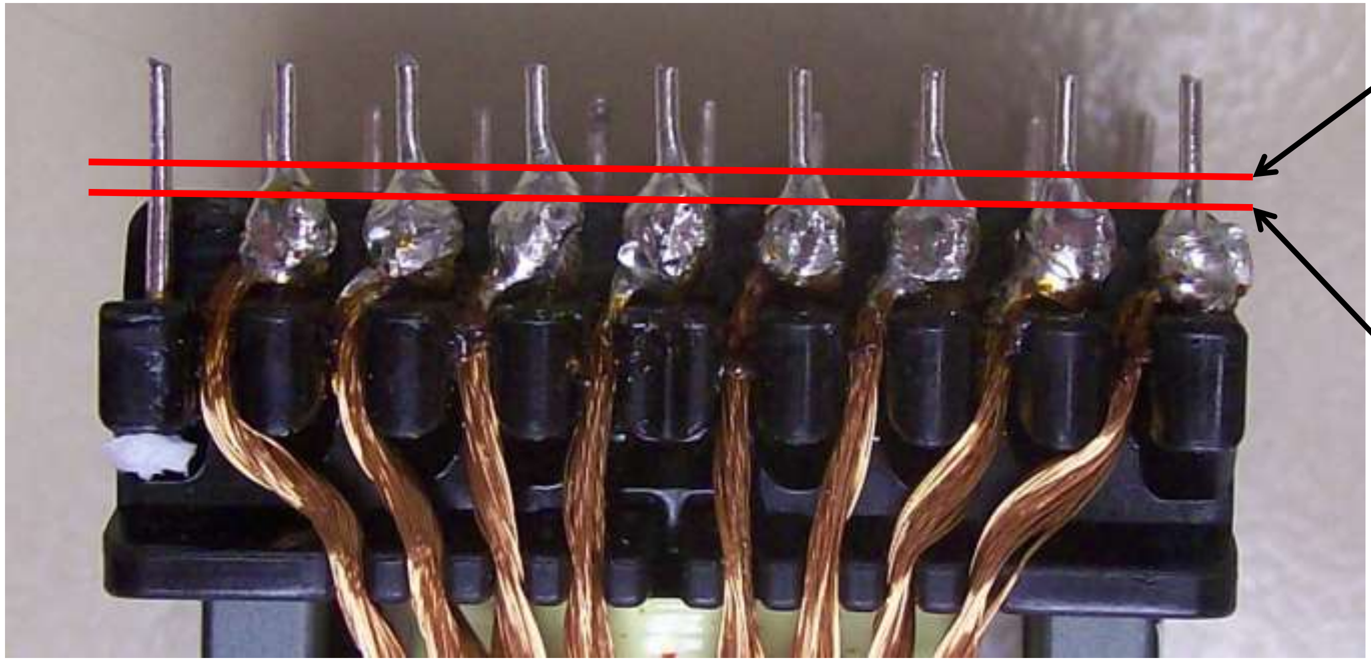
  - Ideally windings on same bobbin rail should be within 3 gauges

- **Sometimes it makes sense to use heavier wire than necessary for soldering – e.g. matching aux wire size to primary, even if current density doesn’t require it (also reduces BOM)**

  - May need two soldering operations if wire mismatch is unavoidable

Solder Terminations

- **Large wire terminations on TH parts can cause height issues**



Large Wire Wraps – this is where part will actually contact PCB

Bobbin Standoff – this surface should contact PCB

To Summarize….

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Design For Manufacturing:

The practice of considering the manufacturing process during the design stage

To increase reliability

To reduce cost and lead time

Involve us as early as possible in design phase!

Thank you!

Please contact:

Stephan Rex – Sales Manager

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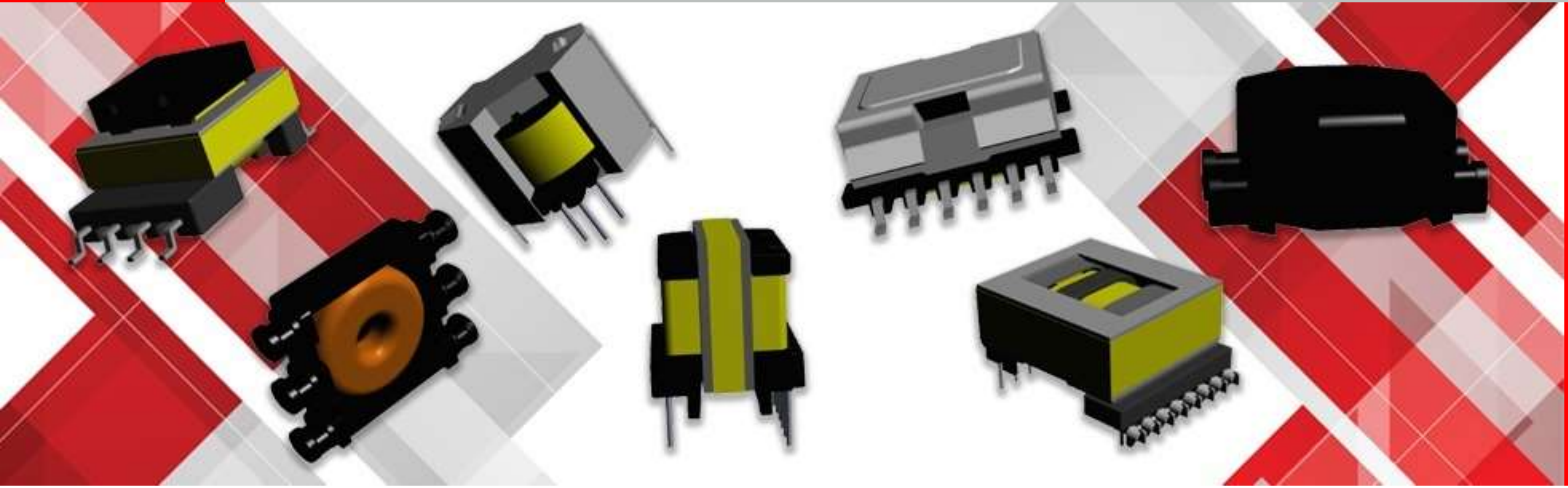
Design for DC Magnetic Immunity



Transformer Parameters

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- **Electrical Specification and Saturation**

ELECTRICAL SPECIFICATIONS @ 25° C unless otherwise noted:

PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	3-5	@20ºC	0.5170 ohms ±10%
D.C. RESISTANCE	9-7	@20ºC	0.0135 ohms ±20%
INDUCTANCE	3-5	10kHz, 100mV, Ls	500.0µH ±10%
SATURATION CURRENT	3-5	20% rolloff from initial	$\boxed{540mA}$
LEAKAGE INDUCTANCE	3-5	tie(9+7),100kHz, 100mV, Ls	42µH typ., 63µH max.
DIELECTRIC	3-9	4000VAC, 1 second	4000VAC, 1 minute
DIELECTRIC	3-core	tie(7+5), 2000VAC, 1 second	
TURNS RATIO		(3-5):(9-7)	17.33:1, ±3%

Magnetic Flux and Core Losses

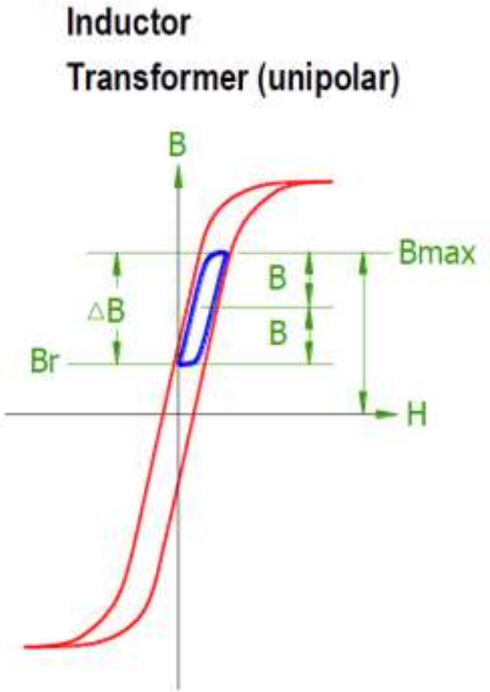
$$P_{Los} \propto f, \Delta B$$

P_{Los} = Core losses

f = frequency

ΔB = Gauss level

Lower ΔB



Magnetic Flux and DC Magnet Effects

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- $$Bsat = \frac{L_{prim} \times I_{peak}}{N_P \times A_e}$$

No DC magnet

- $$Bsat - B_{DCmag} = \frac{L_{prim} \times I_{peak}}{N_P \times A_e}$$

DC magnet

Bsat = Core flux density

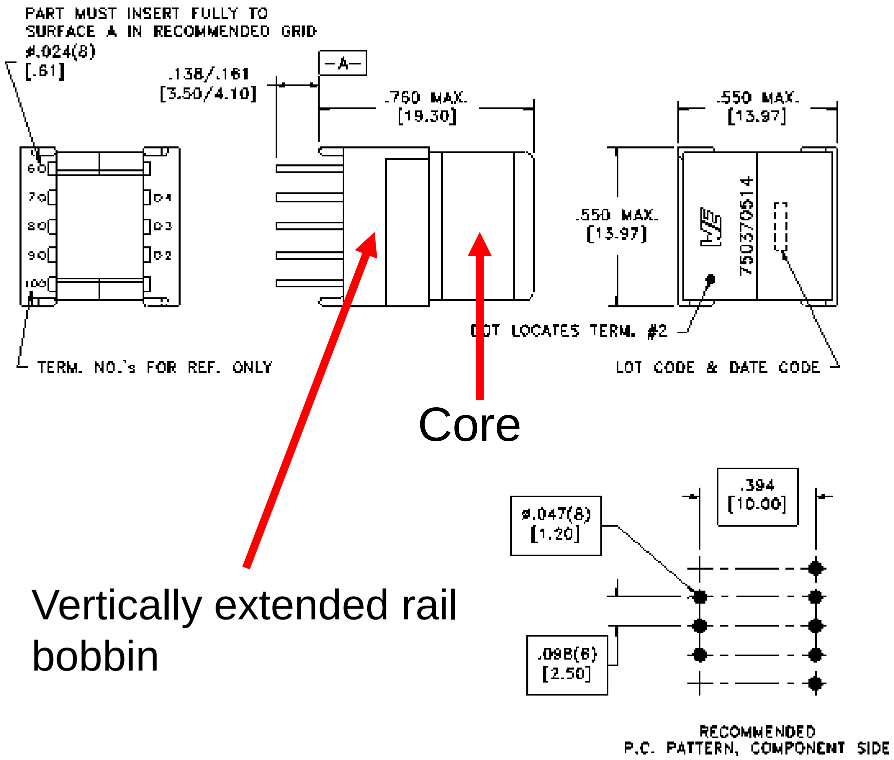
B_{DCmag} = External DC magnetic flux density

Lprim = Primary inductance

Ipeak = Peak primary current

Ae = Core area

How to reduce DC Magnet Effects

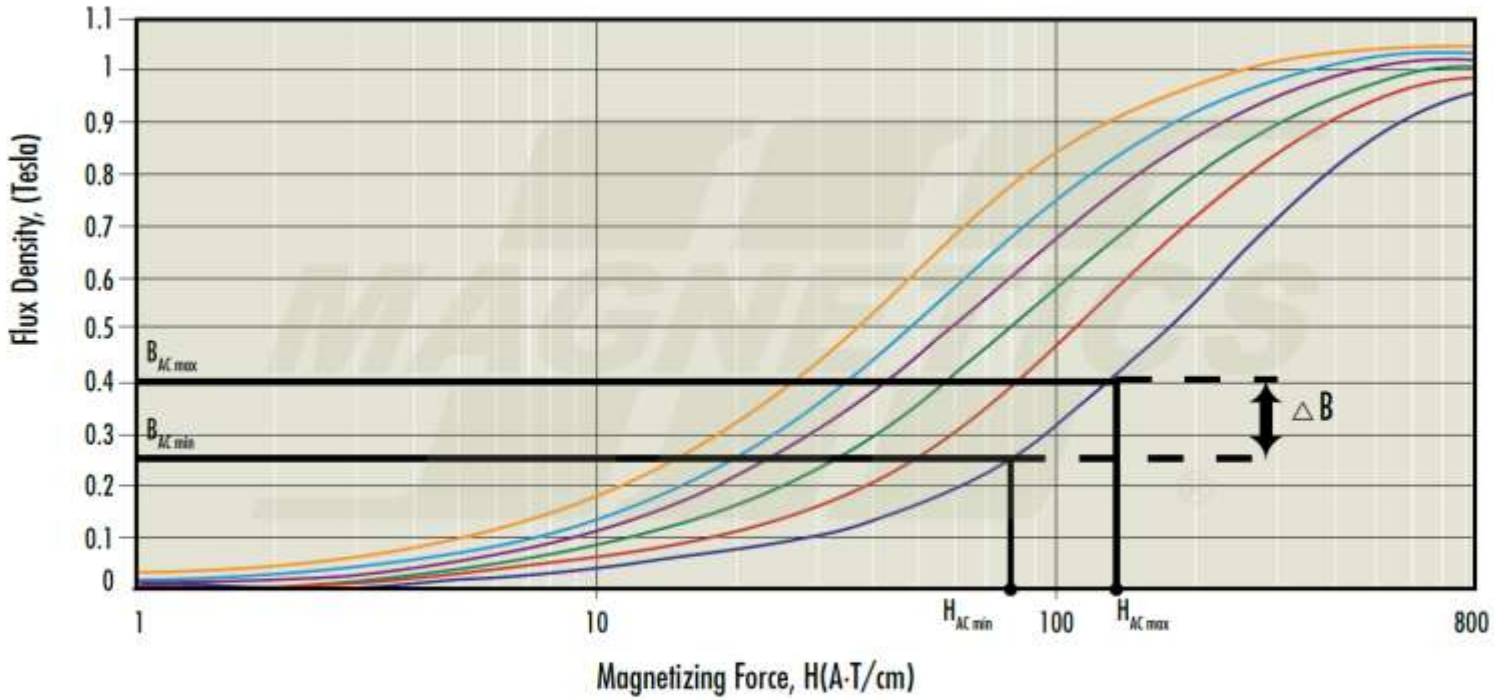


- **Increase physical or electrical distance between DC magnet and transformer core (shielding)**
- **Reduce the Bsat (-B$_{DCmag}$) of the transformer**
  - Increase the number of primary turns
  - Increase the core area
- **Use other core materials**
  - High Bsat materials

$$Bsat - B_{DCmag} = \frac{L_{prim} \times I_{peak}}{N_P \times A_e}$$

Techniques to reduce DC magnet Effects on Transformers

- **Typical B vs. H curve for different μ**



Source: Magnetics technical note, Powder Core Loss Calculation

Examples for soft core materials

- Kool Mμ
- Sendust
- High Flux
- Powdered-iron

Ferrite cores vs Distributed Gap Cores

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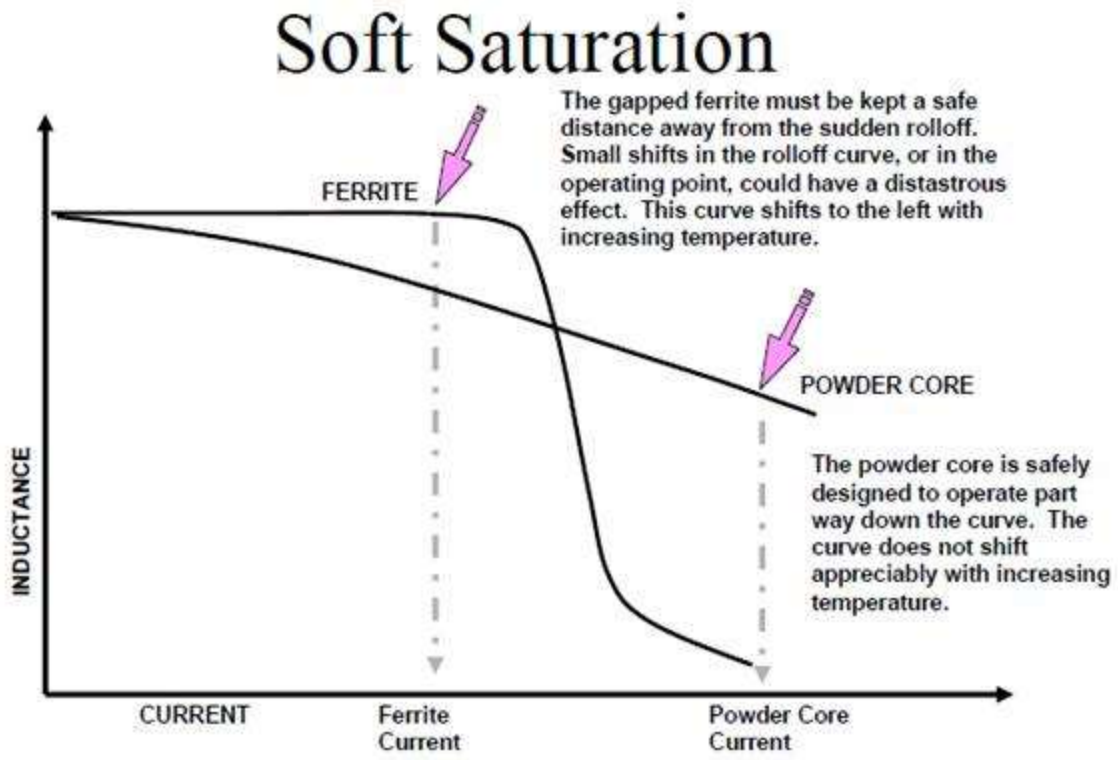

Source: https://www.mag-inc.com/products/powder-cores/learn-more-about-powder-cores

Summary

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- **DC magnetic effects can be reduced by**

  1. Increasing the physical or magnetic path between external DC magent and transformer core (Shielding)

  2. Reducing the transformer gauss level (Increasing the primary turns or core area)

  3. Using cores with high Bsat (Soft saturation)
     - Distributed gap cores
     - Nanocrystalline core materials